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THE PRESENT STATUS OF THE STANDARDS OF THERMAL RADIATION MAINTAINED BY THE BUREAU OF STANDARDS

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ABSTRACT

The basis of the lamp standards of radiation, established and maintained by the Bureau of Standards since 1913, is the black body using the Stefan-Boltzmann constant of total radiation $\sigma = 5.70 \times 10^{-12}$ watt/cm²/deg.⁴

In this paper the present status of the value of the constant of total radiation is reviewed, and it is concluded that, for the present, the basis of the lamp calibration remains unchanged.

These carbon-filament lamp standards of thermal radiation maintained by the Bureau of Standards (S227) were intercompared after a lapse of 12 years and found in good agreement with the original standards which were established in 1913 by direct comparison with a black body.

Two reproductions of these standards which, according to published reports, showed rapid deterioration in radiant flux, were recalibrated. No deterioration, to 2 parts in 840, could be measured in the radiation emitted by one of these lamps which had been in use 8 years. In the other lamp an increase in radiant flux, amounting to about 1 percent, was found. This was caused by a hot spot in the filament, probably resulting from usage or perhaps by injury in shipment.

In a life test, a standard of radiation was operated for 245 hours before an increase in radiant flux became appreciable, and at the expiration of 300 hours this increase amounted to only 0.8 percent.

One section is devoted to the technique of operation, and specific directions are given to insure high precision.

CONTENTS

| | Page |
|--|------|
| I. Introduction | 79 |
| II. Establishment of the reference standards of thermal radiation | 80 |
| III. Intercomparison of the reference standards of thermal radiation | 81 |
| IV. Constancy of lamp standards of thermal radiation | 83 |
| V. Technique of operation | 84 |
| VI. Bibliography | 87 |

I. INTRODUCTION

For the convenience of those who desire to evaluate radiation stimuli in absolute units, during the past two decades the Bureau of Standards has been supplying standards of radiant intensity in the form of seasoned 115-volt carbon-filament incandescent lamps which have been standardized for radiant flux (microwatts per square centimeter).

Before the lamps are calibrated radiometrically they are seasoned and then measured for voltage at three or more designated currents in accordance with the accepted procedure in preparing similar standards of luminous intensity. The maximum voltage is always some 10 percent below the rated voltage.

After the initial seasoning, experience indicates that such lamps are operable for 100 hours or more before they begin to change in radiant flux. Only when the lamps are operated above the calibration voltages is the surface of the filament likely to disintegrate, and only in very rare instances does the filament develop loose contacts at the lead-in wires, which defect is observable from the volt-ampere calibration supplied with the lamp.

At the International Congress on Light, which met in Copenhagen in August 1932, the Committee on Measurement and Standardization of Ultraviolet Radiation Used in Medicine recommended the evaluation of ultraviolet radiation stimuli on a physical (radiometric) basis, in absolute units (1)¹ by means of a nonselective radiometer (thermopile) and filters. The simplest and most reliable procedure for calibrating the radiometer is by means of a standard of thermal radiation. Obviously it would be desirable to use the same kind of standard of radiation in different laboratories, thus eliminating one source of uncertainty.

The object of the present communication is to present the results of an inquiry into the present status of the lamp standards of radiation maintained by this Bureau. Reproductions of these standards are being supplied to the several national laboratories looking forward to the time when there will be an international basis of comparison as now obtains in the lamp standards of luminous intensity.

II. ESTABLISHMENT OF THE REFERENCE STANDARDS OF THERMAL RADIATION

In view of the difficulties in making direct radiometric measurements in absolute value, the original carbon-filament lamp standards of radiation of the Bureau were obtained by direct comparison with a black body (at 1,000° to 1,150° C.), the radiant flux of which was calculated on the assumption that the Stefan-Boltzmann constant of total radiation is $\sigma = 5.7 \times 10^{-12}$ watt/cm²/deg.⁴ (2) (9).

In making this initial comparison the standard lamps were placed at a distance of 1 m from the thermopiles, which were developed with continuous receiving surfaces (7) in order to reduce errors in calibrating them radiometrically. In part of this calibration the thermopiles were sighted alternately upon the black body (distance 30 to 75 cm) and then upon the lamps.

Subsequent measurements upon these lamps, made radiometrically with a thermopile that evaluated the radiant flux in absolute units, and also with a nocturnal radiation instrument, constructed for the United States Weather Bureau (2), showed a close agreement with the direct calibration against the black body.

It was, therefore, assumed that the radiant flux from the standard lamp is known with sufficient accuracy to meet the requirements of workers desiring to evaluate radiation stimuli in absolute units.

Concerning the Stefan-Boltzmann constant of total radiation, the value ($\sigma = 5.70 \times 10^{-12}$ watt/cm²/deg.⁴) used in that calibration is a trifle lower than more recent estimates ($\sigma = 5.71$ to 5.75) of this constant (9) in which corrections have been made for atmospheric absorption. However, the direct measurements (2) which do not

¹ Figures in parentheses here and throughout the text indicate references and notes given in the bibliography at the end of this paper.

depend upon the Stefan-Boltzmann constant, show no systematic difference from the initial comparison of the lamps against the black body in which the Stefan-Boltzmann constant was utilized.

From a recent survey of this question (9) it appears that the value ² of the constant of total radiation ($\sigma = 5.70 \times 10^{-12}$ watt/cm²/deg.⁴), which formed the basis of the lamp calibration long before the more accurate determinations of this constant were available, is so close to the true value that it needs no consideration at the present time.

III. INTERCOMPARISON OF THE REFERENCE STANDARDS OF THERMAL RADIATION

The lamps issued as standards of thermal radiation, in absolute units, are seasoned in lots of 25 to 50. Those that qualify for constancy are marked for orientation, and the voltages are then measured at designated currents by means of the potentiometer outfit used in calibrating lamp standards of luminous intensity.

From each lot of calibrated lamps several are selected and added to the group of reference standards of radiation which, thereafter, are used only infrequently. Those in the earliest sets are rarely used. During the past 20 years, in addition to its working standards, this Bureau has accumulated and placed in reserve a group of 20 lamps as reference standards.

The first lot of 16 lamps that qualified for constancy, after seasoning, were calibrated directly against a black body as already described (2), and, of this group, lamps C-1, 2, 3, 12, 14, and 17 were set aside as reference standards. Five years later (1918) an intercomparison of lamps C-1, 2, 3, 12, 14, and 17, operated on 0.400 ampere, showed a deviation of 0 to 3 parts in 1,000 from the values of the radiant flux assigned to each lamp in 1913, which deviation is entirely within the errors of observation.

In October 1930, before undertaking a calibration of a new lot of lamps, the thermopile-galvanometer outfit was standardized (by R. Stair and J. M. Hogue) against all the standards which had been set aside up to that time, including the group of three lamps (C-1, 2, and 3) which had not been used for 12 years (1918). As shown in columns 4 and 6 of table 1 the average radiation sensitivity (galvanometer deflection) of the thermopile-galvanometer outfit, for the 9 standard lamps, was 1 cm deflection = $4.086 \mu\text{w}/\text{cm}^2$, with a maximum deviation of 3 parts in 1,000, which is entirely within the experimental error of observation.

²The value of the Stefan-Boltzmann constant, determined with an absolute thermopile (2) after a recalculation (9) of all the observational data (using 10 copies of the same type of radiometer), taking into consideration all losses by reflection from the receivers as well as atmospheric absorption is $\sigma = (5.722 \pm 0.012) \times 10^{-12}$ watt/cm²/deg.⁴. This value contains two sets of data which depart by ± 2.8 percent from the mean of 20 sets of measurements, involving a total of about 600 separate determinations. Hence, these two sets have but little effect upon the average value.

The discussions, which emphasize the fact that this value of the radiation constant contains two extreme values, overlook the fact that the few wide departures from the mean value have the merit of showing the extreme range that is possible when use is made of a large number of copies (in this case 13 in all; several were known to be defective) of a particular type of radiometer. Since the observed value of the constant σ , may be systematically too high or too low, a good agreement among a few sets of measurements, made with one or two copies of a particular type of radiometer, is not a sufficient criterion for determining the accuracy of the absolute value. High precision in a few sets of readings is not necessarily an indication of the true value of the measurement.

A recent determination of the constant of total radiation by Hoare (Phil. Mag., vol. 13, p. 380, 1932) using a Callendar radiobalance, gives a value of $\sigma = 5.736 \times 10^{-12}$ watt/cm²/deg.⁴.

In a recent discussion of this subject, Birge (Phys. Rev., vol. 40, p. 207, 1932) points out that the directly observed values which range up to $\sigma = 5.79$, are inconsistent with the results derived indirectly by various equally reliable methods, which indicate a value of $\sigma = 5.714$. From this it appears that the calibration of the standards of radiation against a black body on the basis of $\sigma = 5.70$ is not far from the truth.

A comparison of columns 2 and 3 of this table shows that, within the above limits, there is no systematic difference in the radiation emitted by these lamps. Furthermore, the deviations of 0 to 3 parts in 1,000 are not systematically different from those observed on the same lamps when examined in 1918.

All the reference standards, selected from the different lots of new lamps are in close agreement, electrically and radiometrically, with the lamps originally calibrated against a black body. In addition to these reference standards, there are working standards for use in the laboratory. The "instructions" that are always supplied with the standards of thermal radiation (a pair of which should be used for certainty) suggest that the users likewise should provide themselves with working standards.

If a rapid deterioration took place in this type of lamp, as reported by Leighton and Leighton (3), it would have been observed long ago in the extensive intercomparisons of similar lamps when used as working standards of luminous intensity. It was because of the fact that this type of lamp was known to remain practically constant for 100 hours or more after the initial seasoning (10) that it was selected as a simple, convenient primary standard of thermal radiation in preference to flame standards (2). While its wide usage was only dimly foreseen, from the beginning it was realized that, owing to variations in atmospheric humidity, there would be small variations in the radiant flux. However, owing to absorption by the glass bulb, only a small amount of the total radiation emitted by such a lamp filament is of wave lengths longer than 4μ . Hence, since atmospheric absorption by CO_2 and water vapor is weak for infrared wave lengths shorter than 4μ , this error is probably small and negligible in comparison with other errors. This is supported by the fact that no marked variation in transmission through 1 to 2 m of air has been observed, assuming that the inverse square law holds for the radiation from a lamp filament.

TABLE 1.—*Determination of the radiation sensitivity of a thermopile-galvanometer radiometer in absolute units ($\mu\text{w}/\text{cm}^2$) by comparison with a series of carbon filament lamp standards of thermal radiation, operated on 0.400 ampere*

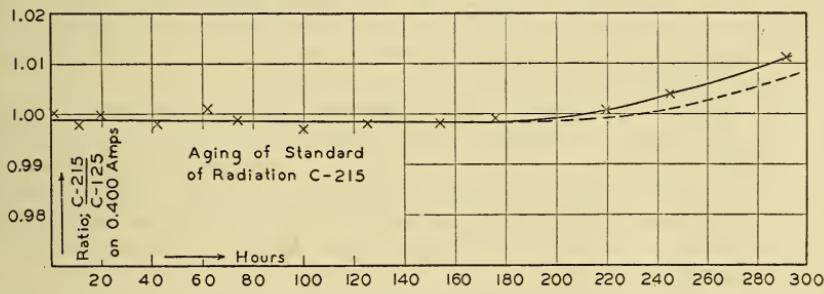
| Lamp 1 | Radiant flux at 2 m | Galva- nometer deflection 2 | Radiant flux to pro- duce 1 cm deflection 3 | Deviation from the average value 5 | Deviation from aver- age 6 |
|-----------|---------------------------|--------------------------------------|---|--|-------------------------------------|
| | $\mu\text{w}/\text{cm}^2$ | cm | $\mu\text{w}/\text{cm}^2$ | $\mu\text{w}/\text{cm}^2$ | pts/1,000 |
| C-1 | 89.9 | 22.06 | 4.075 | -0.011 | -3 |
| C-2 | 83.3 | 20.39 | 4.085 | -0.001 | 0 |
| C-3 | 92.0 | 22.55 | 4.080 | -0.006 | -1 |
| C-17 | 89.0 | 21.72 | 4.098 | +0.012 | +3 |
| C-62 | 83.7 | 20.46 | 4.090 | +0.004 | +1 |
| C-73 | 81.7 | 20.03 | 4.079 | -0.007 | -2 |
| C-84 | 83.9 | 20.55 | 4.083 | -0.003 | -1 |
| C-85 | 86.2 | 22.00 | 4.100 | +0.014 | +3 |
| C-92 | 86.6 | 21.21 | 4.083 | -0.003 | -1 |
| Average | | | 4.086 | | |

IV. CONSTANCY OF LAMP STANDARDS OF THERMAL RADIATION

In this test two standards of thermal radiation, lamps C-125 and C-215, were rigidly mounted, side by side, at a fixed distance (2 m) from the thermopile. The rigid mounting was used to eliminate small, but unavoidable errors that occur in resetting the lamps. Lamp C-125 was used only for determining the radiation sensitivity of the thermopile-galvanometer radiometer, which varies slightly from day to day, and even during the day.

The radiant flux of lamp C-215, relative to that of lamp C-125, used as a standard, was determined after it had been burned, on 0.400 ampere (98.5 volts), for various intervals, amounting to a total of 296 hours. The milliammeter and the voltmeter were in circuit only while measurements were being made.

After operating C-215 for 62 hours, two sets of measurements, made on different days, were found in agreement to 1.5 parts in 1,000 with the average of the measurements made during the first 2 hours, and to within 1 part in 1,000 with the average of all the measure-



(FIGURE 1.)

ments made during the 62 hours. As shown in figure 1, these measurements include two poor sets (at 20 and 62 hours) obtained on windy days.

Not finding a definite change in the radiant flux on operating the lamp for 62 hours the radiometric procedure was then improved by keeping the galvanometer mirror adjusted on the zero of the scale reading (6) and by making a total of 7 sets of readings on the two lamps—4 sets on lamp C-215 with 3 intervening sets on lamp C-125 making (since each set included 15 galvanometer readings) a total of 105 observations, at the expiration of each period of burning.

The measurements, beginning at 74 hours' operation of the lamp and extending to 176 hours, showed no certain change in radiant flux (see fig. 1); and only after about 245 hours operation did an increase in radiant flux (on 0.400 ampere) become appreciable. The burning of the lamp was therefore continued to 291 hours (plus about 5 hours used in observations) when the increase in radiant flux appeared unmistakable. The lamps were then dismounted for a new volt-ampere calibration.

The result of this recalibration showed that the volt-ampere relation of the unused standard lamp C-125 remained unchanged, whereas the voltage of lamp C-215 after 296 hours' operation on 0.400 ampere had increased from 98.3 to 98.5 volts, or about 0.2 percent.

The dotted part of the curve in figure 1 indicates the change in radiant flux of lamp C-215, when the measurements are corrected for the same energy input in the lamp instead of for the same current (0.400 ampere). Even on this basis the increase in radiant flux of lamp C-215 by 300 hours' operation is less than 0.8 percent.

While this is a test of the constancy of but one lamp which may have shown an unusually good performance, numerous checks on our working standards and prolonged investigations of such lamps as standards of luminous intensity (10) indicate that, when properly used, the carbon filament lamp provides a satisfactory means for calibrating radiometers.

Seasoned tungsten-filament lamps have also been tried as standards, one objection to the use of which is the central glass support which may screen part of the incandescent filament.

Certain standards of radiation from this Bureau (viz, C-39 and C-40 issued in 1924 and C-69 in 1928) were reported by P. A. and W. G. Leighton (3) to deteriorate at the rate of about 0.5 percent per hour. In the case of lamp C-39, the decrease in radiant flux was reported to amount to 3.1 percent after burning 9 hours. These lamps were recalled and subjected to radiometric tests, using this Bureau's type of linear thermopile of bismuth-silver (7), connected with a highly shielded Thomson galvanometer (8), also with a high-sensitivity Weston d'Arsonval galvanometer.

Recalibration of lamp C-39 showed that it had not changed appreciably since its original calibration in 1924 (certified value $84.3 \mu\text{w}/\text{cm}^2$; present value $84.1 \mu\text{w}/\text{cm}^2$). Lamp C-69 was found to have a defective filament, easily observed visually. When recalibrated it showed an increased radiant flux over the initial calibration value of about 1 percent. Eleven hours' burning increased this by another percent.

Considered as a whole, there is no evidence, either radiometrically or from many years of investigation of such lamps as standards of light (10) indicating a deterioration of 0.5 percent per hour. The defect found in lamp C-69, though unusual and unavoidable, shows the importance of keeping such lamps properly inspected and using them only for reference standards, against which working standards are compared.

V. TECHNIQUE OF OPERATION

The carbon filament lamp standards of radiation, as already stated, are issued because years of experience in their use as standards of light (10), and as sources in optical pyrometry, show that they are more dependable and constant than any other means of standardization yet attempted.

They provide a simple and accurate means for calibrating photoelectrical and photochemical dosage intensity meters (4), and radiation stimuli used in biological (5) or photochemical problems.

Of the 180 or more standard lamps, issued during the past 20 years, the first intimation of unsatisfactory performance, as noted, appeared during the past year (3).

From the foregoing tests of these particular lamps, it appears that the unsatisfactory performance was more likely in the auxiliary apparatus than in the lamps.

For example, as stated in the instructions issued with each lamp, owing to slow warming of the glass bulb and the support of the filament, the radiation emitted will increase (rather than decrease) slightly in intensity during the first 5 minutes after starting. It is consequently difficult to attribute the observed decrease in intensity (reported to be 0.5 percent per hour, at least on first operation) (3) to a change in the lamp, rather than to a decrease in the radiation sensitivity of the radiometric outfit. For it is commonly observed, at the beginning of a series of measurements, especially if the radiometric apparatus has not been used for some time, that the radiation sensitivity is subject to a small change. In our experience, the constancy (of the sensitivity) of the radiometric outfit is less reliable than the lamp. Unless the laboratory is favorably situated, traffic and meteorological conditions must be unusually steady to permit radiometric measurements with this type of instrument (thermopiles in air) to an absolute accuracy much higher than 1 percent. Although the actual measurements may appear more precise (12), high precision in a set of measurements does not necessarily indicate high accuracy in absolute value.

A change in radiation sensitivity may result from a number of causes: (a) Fatigue of the d'Arsonval galvanometer suspension when deflections are large and in only one direction; (b) lack of uniformity of the galvanometer field, accompanied with a shift of the zero reading³; (c) heating of the thermopile junctions by the Peltier current; (d) change in temperature conditions between the shutter and the background of the lamp; (e) creeping of the zero reading of the ammeter; and (f) a general "warming up" of the whole radiometric outfit which probably includes a number of unexplained factors.

In the days when bolometers were used some of these difficulties were overcome, unknowingly, by keeping the bridge balanced by suitable shunts in the battery circuit. In precise radiometry with a thermopile, which in itself requires no impressed emf, the simplest procedure to keep the circuit balanced is to introduce an auxiliary control current, from a dry battery, through an external circuit (6).

In regard to the standard itself, as is well known, the radiation from an incandescent lamp is not uniform in all directions; hence, the bulb is marked for alignment with respect to the radiometer. If the filament becomes obviously displaced relative to these marks on the bulb (which happened on one occasion) in shipping, or by rough usage in the laboratory, the certified calibration cannot, of course, be depended on. The lamp with displaced filament, mentioned above, retained its volt-ampere relationship but was 3.4 percent above calibration value in radiant flux.

Specific instructions for mounting and using standards of radiation are sent with each lamp. These include the alignment of the lamp with the radiometer, which is accomplished by screwing the lamp into a socket (approved by underwriters) that is held in an upright support. This permits adjusting the lamp about a vertical axis, but which cannot reflect light into the radiometer. The socket itself need not be shielded from the radiometer, but the inside should be inspected to ascertain that the insulation has not become defective.

³ For example, caused by a change of level or rotation of the coil in the field of the permanent magnets, or by rotation of the astatic magnet system in the field of the control magnets of a highly shielded Thomson galvanometer.

The calibration is based on the whole incandescent lamp being exposed to the radiometer. Sufficient time (about 5 minutes) must be allowed for the glass base which supports the filament to attain a uniform temperature before starting the radiometric readings, otherwise errors will be introduced into the energy measurements. In order to reduce this heating, the lamp is purposely supported "base down."

In cleaning the bulb the glass may become electrified by rubbing, and cause the filament to adhere to it. Hence, before lighting the lamp, it should be ascertained that the filament does not adhere to the glass.

To eliminate errors arising from heating by the lamp, the shutter (about 15 by 20 cm) used between the lamp and the thermopile consists of two sheets of aluminum, between which is mounted a sheet of asbestos about 5 mm thick. The side of this shutter toward the lamp is unpainted and kept highly reflecting to reduce absorption of radiation from the lamp. The side toward the radiometer is painted a dull black to minimize reflection.

Other precautions of advantage are: A black cloth, about 1 m square should be placed at a distance of about 1 m to the rear of the standard lamp; and an opaque (heavy cardboard) shield about 1 m square, with an open window about 10 cm wide and 15 cm high, should be placed about 25 cm in front of the lamp. Facing the opening in this shield, the radiometer is placed at a distance of 1 or 2 m from the lamp.

The shutter is mounted between the shield and the lamp, preferably close to the shield. This maintains constant temperature conditions between the radiometer and the shield when the shutter is opened and closed.

Before lighting the lamp, the amount of radiation falling upon the radiometer from the background of the lamp is determined by opening and closing the shutter. This test may be applied at any time provided the lamp has been given sufficient time to come to room temperature. The correction to the observed galvanometer deflection may be positive or negative depending upon the temperature of (radiation from) the background relative to that of the shutter.

It is desirable to make the measurements in a dimly lighted room, to avoid errors from changing sunlight, falling upon the thermopile or surroundings, thus varying the temperature and causing air currents near the radiometer.

The best results are to be obtained by operating the lamp between the certified maximum and minimum calibration values of current or voltage. If the measurement of current be made when a voltmeter is connected across the terminals of the lamp, a correction may have to be made for the part of the current shunted around the lamp. To avoid changes in voltmeter and ammeter calibrations, these instruments should be placed in the same direction (N-S) as when calibrated and no iron or rheostats should be nearer than 50 cm.

It may be stated in conclusion that the evaluation of the radiation stimulus in absolute units, as given in the Bureau's calibration is probably as accurate as the numerous other factors that enter present-day applications. When these other uncertainties have been overcome, it will be desirable to increase the accuracy of the radiometric evaluation either by null methods, in which the galvanometer is

used merely as an indicator (rather than as a precision electric current meter as now used); or, by evaluation of the radiation stimulus by means of an absolute thermopile (2) calibrated directly against a black body instead of using it to determine the Stefan-Boltzmann constant.

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11. According to a recent estimate by Dr. W. G. Leighton the total time that lamp C-39 had been operated was 35 hours, and lamp C-69 for $5\frac{1}{4}$ hours.
12. Without desiring to be pessimistic one of the writers (W.W.C.), after over 3 decades of experience in radiometry, ventures the suggestion that workers in this field should feel happy if they can attain anywhere near this accuracy (viz, 1 percent).

WASHINGTON, May 10, 1933.

